

ENCYCLOPEDIA
of GEOCHEMISTRY

Kluwer Academic Encyclopedia of Earth Sciences Series

ENCYCLOPEDIA OF GEOCHEMISTRY

Aim of the Series

The Kluwer Encyclopedia of Earth Sciences Series provides comprehensive and authoritative coverage of all the main areas in the Earth Sciences. Each volume comprises a focused and carefully chosen collection of contributions from leading names in the subject, with copious illustrations and reference lists.

These books represent one of the world's leading resources for the Earth Sciences community. Previous volumes are being updated and new works published so that the volumes will continue to be essential reading for all professional earth scientists, geologists, geophysicists, climatologists, and oceanographers as well as for teachers and students.

See the back of this volume for a current list of titles in the Encyclopedia of Earth Sciences Series.

Series Editors

Professor Rhodes W. Fairbridge has overseen 31 Encyclopedias in the Earth Sciences Series and has been associated with the Series since its inception. During his career he has worked as a petroleum geologist in the Middle East, been a WWII intelligence officer in the SW Pacific and led expeditions to the Sahara, Arctic Canada, Arctic Scandinavia, Brazil and New Guinea. He is currently Emeritus Professor of Geology at Columbia University and is affiliated with the Goddard Institute for Space Studies.

Professor Michael R. Rampino has published more than 70 papers in professional journals including *Science*, *Nature*, and *Scientific American*. He has worked in such diverse fields as volcanology, planetary science, sedimentology, and climate studies, and has undertaken field work on six continents. He is currently Associate Professor of Earth and Environmental Sciences at New York University and a consultant at NASA's Goddard Institute for Space Studies.

Volume Editor

Clare P. Marshall has worked in the Earth Sciences for 15 years. Her experience in geochemistry ranges from trace element analysis to mineralogical investigations, and she is closely involved in the Association of Women Geoscientists. Clare currently runs a geoscience computer consultancy from her home in Colorado.

ENCYCLOPEDIA OF EARTH SCIENCES SERIES

ENCYCLOPEDIA
of GEOCHEMISTRY

edited by

CLARE P. MARSHALL and
RHODES W. FAIRBRIDGE



KLUWER ACADEMIC PUBLISHERS
DORDRECHT | BOSTON | LONDON

A C.I.P. Catalogue record for this book is available from the Library of Congress.

ISBN 0-412-75500-9

Published by Kluwer Academic Publishers
PO Box 17, 3300 AA Dordrecht, The Netherlands

Sold and distributed in North, Central and South America
by Kluwer Academic Publishers, PO Box 358,
Accord Station, Hingham, MA 02018-0358, USA

In all other countries, sold and distributed
by Kluwer Academic Publishers
PO Box 322, 3300 AH Dordrecht, The Netherlands

Printed on acid-free paper

The cover photograph shows a melanterite deposit forming about 2000 horizontal feet within the Richmond Mine of Iron Mountain, Shasta County, California, USA. Water dripping off of the melanterite stalactite and collected in the plastic beaker has a pH of -0.7. The mine was a copper-zinc-silver-gold mine and once the largest copper producer in the state of California.

Photo Credit: Kirk Nordstrom

Every effort has been made to contact the copyright holders of the figures and tables which have been reproduced from other sources. Anyone who has not been properly credited is requested to contact the publishers, so that due acknowledgement may be made in subsequent editions.

All Rights Reserved

© 1999 Kluwer Academic Publishers

No part of this publication may be reproduced or utilized in any form or by any means, electronic, mechanical, including photocopying, recording or by any information storage and retrieval system, without written permission from the copyright owner.

Printed in Great Britain.

Dedication

This volume is dedicated in appreciation of our respective families. Clare wishes to thank Brian, Laura and Rebecca Marshall for their acceptance of this unusual task their wife and mother determined to complete. Rhodes thanks Dolores Fairbridge, who afforded boundless support and encouragement.

Clare Marshall, Lakewood, Colorado
Rhodes Fairbridge, New York City, New York

Editorial Advisory Board

Dr. Frederick A. Frey

Dept. of Earth Atmospheric and Planetary Sciences 54-1220
Massachusetts Institute of Technology
Cambridge, MA 02139-4307, USA

Dr. William S. Fyse

Dept. of Earth Sciences, B and G Building
University of Western Ontario
London, ON N6A 5B7, Canada

Dr. Alain Yves Huc

Institut Français du Pétrole
BP 311 Rueil Malmaison
F-92506, France

Dr. John Volkman

C.S.I.R.O Division of Oceanography
GPO Box 1538
Hobart, Tasmania 7001, Australia

"When, however, the geologist advances further, and desires to study something more than the mere external forms and physical characters of the materials of which our globe is built up, he is compelled to call in the aid of chemistry, for it is by chemical science alone that he can be enabled to demonstrate the true nature of these materials, to explain their formation or origin, or to discover the causes which have produced the changes or alterations which they have already experienced, or which they may now be undergoing."

D. Forbes
'On the study of chemical geology' *Geological Magazine*, 1868, 5:366–370

Contents

List of Contributors	xix	Argon	18
Preface	xxxiii	<i>Thomas Staudacher</i>	
Acknowledgements	xxxv	$^{40}\text{Ar}/^{39}\text{Ar}$ Dating Method	19
Acid Deposition	1	<i>T. Mark Harrison</i>	
<i>Martin Mihaljević</i>			
Acids and Bases	2	Arsenic	21
<i>Carl O. Moses</i>		<i>Jenny G. Webster</i>	
Actinium	5	Astatine	23
<i>Cynthia E.A. Palmer</i>		<i>Ronald S. Kaufmann</i>	
Activation Energy, Activation Enthalpy, Activation Volume	5	Atomic Absorption Spectrometry	23
<i>Thomas J. Wolery</i>		<i>Philip J. Potts</i>	
Activity and Activity Coefficients	7	Atomic Mass Unit, Avogadro Constant and Mole	23
<i>Thomas J. Wolery</i>		<i>Cesare Emiliani (deceased)</i>	
Aluminum	10	Atomic Number	25
<i>Philippe Ildefonse</i>		<i>Russell S. Harmon</i>	
Americium: Element and Geochemistry	10	Authigenesis	26
<i>David R. Janecky, Wolfgang H. Runde and Mary P. Neu</i>		<i>Rhodes W. Fairbridge</i>	
Analysis: Field Methods	11	Barium	28
<i>R.R. Barefoot</i>		<i>Kathleen S. Smith</i>	
Analytical Geochemistry	12	Berkelium	29
<i>Joaquin Ruiz</i>		<i>Cynthia E.A. Palmer</i>	
Analytical Techniques	13	Beryllium	29
<i>Philip J. Potts</i>		<i>Jeffrey G. Ryan</i>	
Antimony: Element and Geochemistry	15	Biogenic Methane and Gas Hydrate	30
<i>Virgil W. Lueth</i>		<i>Keith A. Kvenvolden</i>	
Aqueous Solutions	16	Biogeochemistry	31
<i>Elizabeth A. Burton</i>		<i>John K. Volkman</i>	
		Biomarker: Aliphatic	31
		<i>Kenneth E. Peters and Clifford C. Walters</i>	

Biomarker: Aromatic <i>Bernd R.T. Simoneit</i>	33	Carbonate Sediments <i>Abigail M. Smith</i>	73
Biomarker: Assessment of Thermal Maturity <i>Kenneth E. Peters</i>	36	Cerium <i>Scott M. McLennan</i>	75
Biomarker: Coals <i>Matthias Radke</i>	39	Cesium <i>David W. Mittelfehldt</i>	76
Biomarker: Higher Plant <i>Bernd R.T. Simoneit</i>	39	Chelation <i>Richard M. Kettler</i>	76
Biomarkers: Lipid, Bacterial Chemical Fossils <i>Michel Rohmer</i>	40	Chemical Kinetics <i>Youxue Zhang</i>	77
Biopolymers and Macromolecules <i>Claude Largeau</i>	42	Chlorine <i>Ronald S. Kaufmann</i>	80
Bismuth: Element and Geochemistry <i>Virgil W. Lueth</i>	43	Chromium <i>Eugene S. Ilton</i>	81
Black Shales and Sapropels <i>Jan Jehlička</i>	44	Clapeyron's Equation <i>Jae-Young Yu</i>	82
Boron <i>Jugdeep Aggarwal</i>	44	Clay Membranes <i>T.M. Whitworth</i>	83
Bromine <i>Ronald S. Kaufmann</i>	49	Clay Minerals: Ion Exchange <i>T.M. Whitworth</i>	85
Cadmium <i>Kathleen S. Smith</i>	50	Coal: Organic Petrography <i>J.C. Shearer and T.A. Moore</i>	87
Calcium <i>David W. Mittelfehldt</i>	51	Coal: Origin and Diagenesis <i>R.M. Bustin</i>	90
Calcium Carbonate and the Carbonic Acid System <i>Sylvia Frisia</i>	51	Coal: Types and Characteristics <i>T.A. Moore and J.C. Shearer</i>	92
Californium <i>Cynthia E.A. Palmer</i>	57	Coal: Vitrinite Reflectance and Maturity <i>Ralf Littke</i>	96
Calorimetry <i>Charles A. Geiger</i>	58	Cobalt <i>Achim Albrecht</i>	97
Carbon <i>Austin Long</i>	58	Colloids <i>Montserrat Filella and Jacques Buffe</i>	98
Carbon-14 Dating and other Applications in Earth Sciences <i>D. Lal and S. Krishnaswami</i>	59	Complexes <i>Helen Mango</i>	99
Carbon Cycle <i>Peter S. Bakwin</i>	65	Compound-Specific Isotope Analysis <i>Roger E. Summons</i>	100
Carbon Isotopes <i>Juha Karhu</i>	67	Copper <i>Mark A. Williamson</i>	101
Carbonate Compensation Depth <i>Elizabeth A. Burton</i>	73	Cosmic Elemental Abundances <i>D. Lal</i>	102
		Cosmogenic Nuclides <i>Eric Thorson Brown</i>	104

Counters <i>Ernest B. Ledger</i>	108	Eh–pH Relations <i>Richard B. Wanty</i>	183
Critical Points <i>Peter A. Rock and William H. Casey</i>	110	Einsteinium <i>Cynthia E.A. Palmer</i>	187
Crystal Chemistry <i>Dana T. Griffen</i>	110	Electrolyte Theory <i>Thomas J. Wolery</i>	187
Crystal Field Theory <i>Hans Keppler</i>	118	Electron Capture <i>Carla W. Montgomery</i>	189
Crystal Growth <i>Youxue Zhang</i>	120	Electron Microprobe <i>C. Wagner</i>	190
Curium: Element and Geochemistry <i>Wolfgang H. Runde, Mary P. Neu and David R. Janecky</i>	123	Electronegativity <i>Jae-Young Yu</i>	191
Dating Methods <i>Brian D. Marshall</i>	124	Elementary Particles <i>R.K. Varma</i>	193
Debye–Hückel Equation <i>Thomas J. Wolery</i>	124	Elements: Actinide Series <i>Benoît Villemant</i>	195
Diagenesis <i>Uwe Brand, Joan O. Morrison and Ian T. Campbell</i>	126	Elements: Alkali and Alkaline Earth <i>David W. Mittlefehldt</i>	198
Differential Thermal Analysis and Scanning Calorimetry <i>James L. Gooding</i>	131	Elements: Chalcophile <i>H. Palme</i>	204
Diffusion <i>K. Stüwe</i>	133	Elements: Distribution <i>Frederick A. Frey</i>	204
Dolomite and Dolomitization <i>Sylvia Frisia</i>	140	Elements: Halogen <i>Ronald S. Kaufmann</i>	207
Dysprosium <i>Scott M. McLennan</i>	142	Elements: Heat-producing <i>Fernando Bea</i>	208
Earth's Atmosphere <i>M.A.K. Khalil</i>	143	Elements: High Field Strength <i>V.J.M. Salters</i>	209
Earth's Continental Crust <i>Scott M. McLennan and Stuart Ross Taylor</i>	145	Elements: Incompatible <i>W. Ian Ridley</i>	210
Earth's Core <i>William F. McDonough</i>	151	Elements: Lanthanide Series, Rare Earths <i>Scott M. McLennan</i>	211
Earth's Formation and Geochemical Evolution <i>H. Palme</i>	156	Elements: Large-ion Lithophile <i>Roberta L. Rudnick</i>	214
Earth's Mantle Geochemistry <i>W. Ian Ridley</i>	162	Elements: Lithophile <i>H.G. Stosch</i>	214
Earth's Ocean Geochemistry <i>Joris M. Gieskes</i>	168	Elements: Metalloids <i>Graeme E. Batley</i>	215
Earth's Oceanic Crust <i>Michael Perfit</i>	179	Elements: Noble Gases <i>Thomas Staudacher</i>	216
		Elements: Platinum Group <i>Sarah-Jane Barnes</i>	218

Elements: Radioactive <i>Paul R. Dixon</i>	219	Fugacity <i>Uwe Brand and Ian T. Campbell</i>	256
Elements: Siderophile <i>H. Palme</i>	221	Gadolinium <i>Scott M. McLennan</i>	257
Elements: Trace <i>M. Elaine Kennedy</i>	222	Gallium: Element and Geochemistry <i>Erich Schroll</i>	257
Elements: Transition <i>L. Galoisy and C. Marshall</i>	223	Gas Chromatography–Mass Spectrometry (GS–MS) <i>Andrew T. Revill</i>	259
Enthalpy <i>Carl O. Moses</i>	226	Gas Source Mass Spectrometry <i>I.P. Wright</i>	261
Entropy <i>Carl O. Moses</i>	227	Geoavailability <i>Kathleen S. Smith</i>	262
Epigenesis <i>Vidojko Jović</i>	232	Geochemical Classification of the Elements <i>Scott M. McLennan</i>	263
Equilibrium <i>Heinz Gamsjäger</i>	232	Geochemical Exploration <i>Arthur W. Rose</i>	266
Equilibrium Constant <i>Erich Königsberger</i>	233	Geochemical Reference Materials <i>K. Govindaraju</i>	269
Erbium <i>Scott M. McLennan</i>	236	Geochemical Tectonics <i>Joaquin Ruiz</i>	270
Europium <i>Scott M. McLennan</i>	236	Geochemical Thermodynamics <i>Peter A. Rock and William H. Casey</i>	271
Experimental Mineralogy and Petrology <i>Charles A. Geiger</i>	237	Geochemistry <i>William S. Fye</i>	277
Exsolution <i>Jae-Young Yu</i>	239	Geochemistry: Low-temperature <i>Elizabeth A. Burton</i>	280
Fermium <i>Cynthia E.A. Palmer</i>	245	Geochemistry of Sediments <i>Scott M. McLennan and Richard W. Murray</i>	282
Fick's Law <i>Ronald S. Kaufmann</i>	245	Geochronology and Radioisotopes <i>Carla W. Montgomery</i>	292
Fission-track Analysis <i>Charles H. Naeser and Nancy D. Naeser</i>	246	Geologic Time Scale <i>R. Michael Easton</i>	295
Fluid–Rock Interaction <i>William E. Glassley</i>	248	Geothermal Systems <i>Steven W. Lonker</i>	298
Fluids in Volcanic and Plutonic Environments: Evidence From Fluid Inclusions <i>B. De Vivo</i>	250	Geothermometers <i>Maurice Pagel and Pierre Barbey</i>	302
Fluorine <i>Ronald S. Kaufmann</i>	252	Geothermometry and Geobarometry <i>Richard F. Wendlandt</i>	305
Francium <i>David W. Mittlefehldt</i>	253	Germanium: Element and Geochemistry <i>Erich Schroll</i>	307
Free Energy <i>Carl O. Moses</i>	253	Gibbs–Duhem Equation <i>Peter A. Rock and William H. Casey</i>	308

Gold <i>Jenny G. Webster</i>	309	Iron <i>Mark A. Williamson</i>	348
Hafnium <i>P. Jonathan Patchett</i>	312	Isotope Dilution <i>Carla W. Montgomery</i>	353
Helium <i>Thomas Staudacher</i>	312	Isotope Fractionation <i>Ian D. Clark</i>	354
Helium Isotopes <i>David W. Graham</i>	314	Krypton <i>Thomas Staudacher</i>	358
Henry's Law <i>Ian T. Campbell and Uwe Brand</i>	315	Laboratory Simulations of Oil and Natural Gas Formation <i>J.S. Seewald and T.I. Eglinton</i>	359
History of Geochemistry <i>Rhodes W. Fairbridge</i>	315	Lanthanum <i>Scott M. McLennan</i>	360
Holmium <i>Scott M. McLennan</i>	322	Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry <i>Douglas L. Miles</i>	360
Hydrocarbons <i>John K. Volkman</i>	323	Lawrencium <i>Cynthia E.A. Palmer</i>	362
Hydrogen <i>Ronald S. Kaufman</i>	325	Lead <i>Martin Mihaljević</i>	362
Hydrogen Isotopes <i>R.V. Krishnamurthy</i>	326	Lead: Stable Isotopes <i>Leon E. Long</i>	363
Hydrologic Cycle <i>Ray Kenny</i>	330	Lipids (Eubacteria and Archeabacteria) <i>Michel Rohmer</i>	368
Hydrothermal Alteration <i>Byron R. Berger</i>	331	Lithium: Element and Geochemistry <i>Ju-chin Chen</i>	369
Hydrothermal Solutions <i>Robert J. Bodnar</i>	333	Luminescence <i>G. Calas</i>	370
Hypogene <i>Vidojko Jović</i>	337	Lutetium <i>Scott M. McLennan</i>	371
Indium: Element and Geochemistry <i>Erich Schroll</i>	339	Lutetium–Hafnium Decay System <i>P. Jonathan Patchett</i>	372
Inductively Coupled Plasma Mass Spectrometry (ICP–MS) <i>Fernando Bea</i>	340	Magmatic Processes <i>Robert L. Cullers</i>	373
Iodine <i>Edward C.V. Butler</i>	341	Magnesium <i>David W. Mittelfehldt</i>	379
Ion Exchange Chromatography <i>Peter van Calsteren</i>	342	Magnetism <i>Guillaume Morin</i>	379
Ion Microprobe <i>Nobumichi Shimizu</i>	343	Manganese <i>Lloyd M. Petrie</i>	382
Ionic Radii <i>Dana T. Griffen</i>	344	Mass Transfer <i>Ross C. Kerr</i>	384

Mendelevium <i>Cynthia E.A. Palmer</i>	387	Nitrogen <i>A. Hall</i>	426
Mercury <i>Martin Mihaljević</i>	387	Nitrogen Cycle <i>Elisabeth A. Holland</i>	428
Metamorphic Environments: Chemical Mobility <i>D.R. Bowes and J. Košler</i>	389	Nitrogen Isotopes <i>Nathaniel E. Ostrom and Peggy H. Ostrom</i>	431
Meteorites <i>Gregory A. Snyder</i>	395	Nobelium <i>Cynthia E.A. Palmer</i>	434
Micro-Raman Spectroscopy <i>Stephen Roberts</i>	400	Nucleosynthesis <i>J.N. Goswami</i>	434
Mid-Ocean Ridge Basalt (MORB) <i>Anton P. le Roex</i>	401	Nutrients <i>J. Faganeli</i>	437
Mineral Defects <i>Annemarie Meike</i>	401	Occurrence of Organic Facies <i>R. Basil Johns</i>	439
Mineral Genesis <i>Alain J. Baronnet</i>	404	Oil Seeps and Coastal Bitumens <i>Andrew T. Revill</i>	441
Mineralogy <i>William S. Fyfe</i>	409	Oil Shales <i>A.T. Revill</i>	441
Molybdenum <i>A.A. Bookstrom</i>	411	Oil–Oil and Oil–Source Rock Correlation <i>Clifford C. Walters</i>	442
Mössbauer Spectroscopy <i>D.G. Rancourt</i>	413	Oklo Natural Nuclear Reactor <i>Mark J. Rigali and Bartholomew S. Nagy</i> <i>(deceased)</i>	444
Natural Gas <i>Alain Prinzhofner</i>	415	Onuma Diagrams	446
Natural Resources <i>Martin Hale</i>	416	<i>Jean M. Richardson</i>	
Neodymium <i>Scott M. McLennan</i>	418	Ore Deposits <i>Martin Hale</i>	447
Neodymium in Igneous Rocks <i>J. Košler</i>	418	Organic Geochemistry <i>John K. Volkman</i>	453
Neodymium in Sedimentary Rocks <i>Carol D. Frost</i>	421	Organic Matter in Fossils <i>Stephen A. Macko and Michael H. Engel</i>	456
Neon <i>Thomas Staudacher</i>	422	Organic Matter in Meteorites <i>Scott Messenger</i>	458
Neptunium: Element and Geochemistry <i>Wolfgang H. Runde, David R. Janecky and Mary P. Neu</i>	423	Organics: Contemporary Degradation and Preservation <i>Stuart G. Wakeham</i>	458
Neutron Activation Analysis <i>James R. Budahn</i>	424	Organics: Sources and Depositional Environments <i>Stuart G. Wakeham</i>	460
Nickel <i>Laurence Galoisy</i>	425	Osmium <i>John W. Morgan</i>	461
Niobium <i>A.M.R. Neiva</i>	426	Oxidation–Reduction <i>Charles G. Patterson</i>	462

Oxygen <i>Steven C. Semken</i>	467	Phosphorus <i>Gerald Matisoff</i>	516
Oxygen Isotopes <i>Ethan L. Grossman</i>	469	Platinum <i>W. Crawford Elliott</i>	516
Paleo-Sea Surface Temperature Estimations: Organic Geochemistry and Paleoclimates <i>Elisabeth L. Sikes</i>	475	Plutonium: Environmental Chemistry and Geochemistry <i>Paul R. Dixon and David B. Curtis</i>	517
Paleoenvironments <i>M. Elaine Kennedy</i>	477	Polonium: Element and Geochemistry <i>Wolfgang H. Runde</i>	518
Paleoproductivity <i>Uwe Brand, Ian T. Campbell and Joan O. Morrison</i>	479	Porphyrins <i>Chris Boreham</i>	519
Paleotemperature <i>Uwe Brand, Joan O. Morrison and Ian T. Campbell</i>	480	Potassium <i>David W. Mittelfelldt</i>	522
Palladium <i>Christopher J. Capobianco</i>	484	Potassium–Argon Dating Method <i>K.A. Foland</i>	522
Paragenesis <i>Robert J. Kamilli</i>	485	Potassium–Calcium Decay System <i>Brian D. Marshall</i>	525
Particle-Induced X-Ray Emission (PIXE) <i>J.L. Campbell</i>	488	Praseodymium <i>Scott M. McLennan</i>	526
Partition Coefficients <i>Robert L. Cullers</i>	489	Precambrian Atmosphere <i>Grant M. Young</i>	526
Peat <i>William Shotyk</i>	490	Precambrian Geochemistry <i>R. Michael Easton</i>	532
Periodic Table <i>Gregory A. Snyder</i>	491	Precambrian Organic Matter <i>Roger E. Summons</i>	535
Petroleum <i>R.G. Schaefer</i>	494	Promethium <i>Scott M. McLennan</i>	537
Petroleum: Hydrothermal <i>Bernd R.T. Simoneit</i>	497	Protactinium <i>David A. Pickett</i>	537
Petroleum: In-reservoir Biodegradation <i>Jacques Connan</i>	498	Quantum Numbers <i>D. G. Rancourt</i>	539
Petroleum: Kinetic Modeling <i>R.G. Schaefer</i>	499	Radioactivity <i>Stephen A. Prevec</i>	540
Petroleum: Primary Migration (Generation and Expulsion) <i>Jean Burrus</i>	500	Radium <i>Arthur W. Rose</i>	541
Petroleum: Surface Geochemistry <i>R.P. Philp</i>	502	Radon <i>Arthur W. Rose</i>	542
Petroleum: Types, Occurrence and Reserves <i>R.G. Schaefer and D.H. Welte</i>	504	Rare Earth Element Tetrad Effect <i>T. Akagi</i>	543
Phase Equilibria <i>Robert W. Luth</i>	505	Remote Sensing <i>David A. Rothery</i>	544
		Rhenium <i>John W. Morgan</i>	547

Rhenium–Osmium Dating Method <i>John W. Morgan</i>	547	Stable Isotopes <i>Ian D. Clark</i>	588
Rhodium <i>R.R. Barefoot</i>	550	Standard States <i>Peter A. Rock and William H. Casey</i>	592
Rock-Eval Pyrolysis <i>Kenneth E. Peters</i>	551	Steroidal Compounds <i>John K. Volkman</i>	593
Rocks <i>Vidojko Jović</i>	554	Stoichiometry <i>R. Hellmann</i>	595
Rubidium: Element and Geochemistry <i>E. Craig Simmons</i>	555	Strontium: Element and Geochemistry <i>E. Craig Simmons</i>	598
Rubidium–Strontium Method <i>Leon E. Long</i>	556	Strontium in Igneous Rocks <i>Jon Davidson</i>	599
Ruthenium <i>R.R. Barefoot</i>	561	Strontium in Sedimentary Rocks <i>Uwe Brand, Joan O. Morrison and Ian T. Campbell</i>	600
Samarium <i>Scott M. McLennan</i>	563	Sulfate Minerals <i>Jeremy P. Richards</i>	603
Samarium–Neodymium <i>Carla W. Montgomery</i>	563	Sulfate Reduction <i>Hans G. Machel</i>	603
Sampling <i>Jean M. Richardson</i>	567	Sulfide Minerals <i>Jeremy P. Richards</i>	605
Scandium <i>Scott M. McLennan</i>	569	Sulfides in Mafic and Ultramafic Magmas <i>Robert D. Francis</i>	606
Scanning Electron Microscope <i>C. Wagner</i>	569	Sulfosalt Minerals <i>Jeremy P. Richards</i>	607
Sedimentary Fluids <i>Ian E. Hutcheon</i>	570	Sulfur <i>Martin A.A. Schoonen</i>	608
Selenium <i>Eugene S. Ilton</i>	571	Sulfur Cycle <i>Martin A.A. Schoonen</i>	608
Silicon, Silica <i>Nancy W. Hinman</i>	572	Sulfur Isotopes in Geochemistry <i>Keith Hannan</i>	610
Silver: Element and Geochemistry <i>Helen N. Mango</i>	576	Supergene <i>Vidojko Jović</i>	615
Sodium <i>David W. Mittlefehldt</i>	578	Surface Geochemistry <i>Christian Ludwig and William H. Casey</i>	616
Soil <i>William S. Fyfe</i>	578	Synchrotron X-Ray Fluorescence Analysis <i>Philip J. Potts</i>	617
Solid Solution <i>Erich Königsberger</i>	580	Syngensis <i>Rhodes W. Fairbridge</i>	618
Solubility <i>Heinz Gamsjäger</i>	583	Tantalum <i>A.M.R. Neiva</i>	620
Spectrophotometry <i>Ian T. Campbell and Uwe Brand</i>	587	Technetium: Environmental Chemistry and Geochemistry <i>Paul R. Dixon and David B. Curtis</i>	621

Tellurium <i>Vidojko Jović</i>	621	Van der Waals Force <i>Jae-Young Yu</i>	655
Terbium <i>Scott M. McLennan</i>	622	Vanadium <i>Gregory A. Snyder</i>	656
Thallium <i>Vidojko Jović</i>	622	Volcanic Gases <i>T.M. Gerlach</i>	656
Thermal Ionization Mass Spectrometry <i>Peter van Calsteren</i>	623	Volcanism <i>Peter W. Francis</i>	658
Thermochemistry <i>Mitchell Schulte</i>	624	Water <i>Carl O. Moses</i>	660
Thermogravimetry <i>Patrick K. Gallagher</i>	626	Water: Fresh <i>Arthur H. Brownlow</i>	667
Thermoluminescence <i>Christophe Falguères</i>	628	Weathering: Chemical <i>Patrick V. Brady</i>	668
Thixotropy <i>H.C. Weed</i>	630	X-Ray Diffraction <i>R.J. Angel</i>	670
Thorium: Element and Geochemistry <i>S. Krishnaswami</i>	630	X-Ray Fluorescence Analysis <i>Philip J. Potts</i>	670
Thulium <i>Scott M. McLennan</i>	635	Xenon <i>Thomas Staudacher</i>	671
Tin <i>A.M.R. Neiva</i>	635	Ytterbium <i>Scott M. McLennan</i>	673
Titanium: Element and geochemistry <i>François Farges</i>	636	Yttrium <i>Scott M. McLennan</i>	673
Trace Element Partitioning Models <i>Roger L. Nielsen</i>	637	Zinc <i>Martin Mihaljević</i>	674
Tritium <i>Austin Long</i>	639	Zirconium: Element and Geochemistry <i>François Farges</i>	675
Tungsten <i>John C. Groen</i>	639	Appendix A: List of entries by subject	676
Uranium: Element and Geochemistry <i>Fernando Bea</i>	645	Appendix B: Alphabetical list of the chemical elements (up to 103)	680
Uranium–Lead Thorium–Lead Decay System <i>P. Vidal</i>	648	Appendix C: The international system of units	682
Uranium Series Disequilibria <i>Michel Condomines</i>	650	Index of authors cited	685
		Subject index	703

Contributors

Jugdeep Aggarwal
Institut für Mineralogie
Universität Münster
Correnstr. 24
D-48149 Münster
Germany

Tasuku Akagi
Faculty of Agriculture
Tokyo University of Agriculture and Technology
3-5-8 Saiwai-cho Fuchu
Tokyo, 183
Japan

Achim Albrecht
EAWAG-ETH
Environmental Physics
Überlandstr. 133
CH-8600 Dü, Bendorf Switzerland

Ross J. Angel
Bayerisches Geoinstitut
Universität Bayreuth
D-95440 Bayreuth
Germany

Peter S. Bakwin
NOAA/CMDL R/E/CG1
Carbon Cycle Group
325 Broadway Boulder, CO 80303
USA

Pierre Barbe
CREGU
3, rue Bois de Champelle, B.P. 23
F-54501 Vandoeuvre-les Nancy
France

Boron

R. R. Barefoot
Department of Geology
University of Toronto
Toronto, ON M5S 3B1
Canada
Analysis: field methods; Iridium; Rhodium; Ruthenium

Rare earth elements tetrad effect

Sarah J. Barnes
Universite du Quebec a Chicoutimi
Module des Sciences de la Terre
Chicoutimi, PQ G7H 2B1
Canada

Elements: platinum group

Cobalt

Alain Baronnet
CRMC2 CNRS
Campus de Luminy – Case 913
F-13288, Marseille Cedex 9
France

Mineral genesis

X-ray diffraction

Graeme E. Batley
C.S.I.R.O. Division of Coal and Energy Technology
Lucas Heights Laboratory
Private Mail Bag 7
Menai, NSW 2234
Australia

Elements: metalloids

Carbon cycle

Fernando Bea Fac. de Ciencias, Petrology Campus Fuentenueva E-18002 Granada Spain	<i>Elements: heat producing; Inductively coupled plasma mass spectrometry; Uranium</i>	Eric Thorson Brown Large Lakes Observatory University of Minnesota Duluth, MN 55812 USA	<i>Cosmogenic nuclides</i>
Byron R. Berger US Geological Survey Denver Federal Center MS 973 Denver, CO 80225-0046 USA	<i>Hydrothermal alteration</i>	Arthur H. Brownlow Boston University Department of Earth Sciences Boston, MA 02215 USA	<i>Water: fresh</i>
Robert J. Bodnar Fluids Research Laboratory Department of Geological Sciences Virginia Polytechnic Institute and State University Blacksburg, VA 24061 USA	<i>Hydrothermal solutions</i>	James R. Budahn US Geological Survey Denver Federal Center PO Box 25046, MS 974 Lakewood, CO 80225 USA	<i>Neutron activation analysis</i>
Art Bookstrom US Geological Survey West 904 Riverside, Rm 202 Spokane, WA 99201-1087 USA	<i>Molybdenum</i>	Jacques Buffle Department of Inorganic, Analytical and Applied Chemistry University of Geneva 30, Quai Ernest Ansermet CH-1211 Geneva 4 Switzerland	<i>Colloids</i>
Christopher J. Boreham AGSO G.P.O. Box 378 Canberra, ACT 2601 Australia	<i>Porphyrins</i>	Jean Burrus Technical Director BEICIP-FRANLAB Boite Postale 213 F-92502 Rueil Malmaison Cedex France	<i>Petroleum: primary migration (generation and expulsion)</i>
Donald R. Bowes Division of Earth Sciences University of Glasgow Glasgow, G12 8QQ Scotland	<i>Metamorphic environments: chemical mobility</i>	Elizabeth A. Burton Northern Illinois University Department of Geology De Kalb, IL 60115-2854 USA	<i>Aqueous solutions; Carbonate compensation depth; Geochemistry: low-temperature</i>
Patrick V. Brady Sandia National Laboratories MS-750 Albuquerque, NM 87185-0750 USA	<i>Weathering: chemical</i>	R. M. Bustin Department of Earth and Ocean Science The University of British Columbia 6339 Stores Road Vancouver BC, V6T 1Z4 Canada	<i>Coal: origin and diagenesis</i>
Uwe Brand Brock University Geological Sciences St. Catherines ON, L2S 3A1 Canada	<i>Diagenesis; Fugacity; Henry's law; Paleoproductivity; Paleotemperatures; Spectrophotometry; Strontium in sedimentary rocks</i>	Edward C. V. Butler C.S.I.R.O. Division of Oceanography GPO Box 1538 Hobart, Tasmania 7001 Australia	<i>Iodine</i>

Georges Calas Université Paris 6, Laboratoire de Minéralogie Institut Physique du Globe de Paris Tour 16/2, 4, place Jussieu F-75251 Paris Cedex 05 France	Jacques Connan Elf Aquitaine Production CST Jean Feger – L2 109 Avenue Larribau F-64018 Pau Cedex France
	<i>Petroleum: in-reservoir biodegradation</i>
Ian T. Campbell Brock University Department of Earth Sciences St. Catherines ON, L2S 3A1 Canada	Robert L. Cullers Kansas State University Department of Geology Thompson Hall Manhattan, KS 66506 USA
	<i>Magmatic processes; Partition coefficients</i>
J. L. Campbell Department of Physics University of Guelph Guelph, ON, N1G 2W1 Canada	David B. Curtis Isotope and Nuclear Chemistry Division Los Alamos National Laboratory University of California Los Alamos, NM 87545 USA
	<i>Elements: radioactive; Plutonium; Technetium</i>
Christopher J. Capobianco Lunar & Planetary Laboratory University of Arizona Tucson, AZ 85721 USA	Jon Davidson University of California Department of Earth and Space Sciences Los Angeles, CA 90024 USA
	<i>Strontium in igneous rocks</i>
William H. Casey University of California, Davis Department of Land, Air and Water Research 151 Hoagland Hall Davis, CA 95616 USA	Benedetto De Vivo Geofisica e Vulcano Largo S. Marcellino 10 I-80138 Napoli Italy
	<i>Fluids in volcanic and plutonic environments</i>
Ju-chin Chen Institute of Oceanography National Taiwan University P. O. Box 23-13 Taipei, Taiwan ROC	Paul R. Dixon Isotope and Nuclear Chemistry Division Los Alamos National Laboratory University of California Los Alamos, NM 87545 USA
	<i>Elements: radioactive; Plutonium; Technetium</i>
Ian D. Clark University of Ottawa, Geology 161 Louis Pasteur Ottawa ON, K1N 6N5 Canada	R. Michael Easton Ontario Geological Survey 2036 Armstrong Street Sudbury ON, P3E 4W1 Canada
	<i>Geologic time scale; Precambrian geochemistry</i>
Michel Condomines CNRS UMR 6524 Université Blaise Pascal 5, rue Kessler F-63038 Clermont-Ferrand Cedex France	T. I. Eglinton Woods Hole Oceanographic Institution Department of Marine Chemistry and Geochemistry Woods Hole, MA 02543 USA
	<i>Laboratory simulations of oil and natural gas formation</i>

W. Crawford Elliott
Department of Geology
Georgia State University
Atlanta, GA 30303
USA

Platinum

Cesare Emiliani (deceased)

Atomic mass unit; Avogadro constant and mole

Michael H. Engel
University of Oklahoma
School of Geology and Geophysics
100 East Boyd, 810 Energy Center
Norman, OK 73019-0628
USA

Organic matter in fossils

Jadran Faganeli
University of Ljubljana
Marine Biological Station Piran
Fornace 41, 66330 Piran
Slovenia

Nutrients

Rhodes W. Fairbridge
420 Riverside Drive, Apartment 2B
New York, NY 10025
USA

Authigenesis; History of geochemistry; Syngensis

Christophe Falguères
Institut de Paléontologie Humaine
1, rue René Panhard
F-75013 Paris
France

Thermoluminescence

François Farges
IFI – Université de Marne la Vallée
2 rue de la Butte Verte
F-93166 Noisy le Grand Cedex
France

Titanium; Zirconium

Montserrat Filella
Department of Inorganic, Analytical and Applied Chemistry
University of Geneva
30, Quai Ernest Ansermet
CH 1211 Geneva 4
Switzerland

Colloids

Kenneth A. Foland
Ohio State University
Department of Geological Sciences
291 Watts Hall, 104 West 19th Ave.
Columbus, OH 43210-7688
USA

Potassium–argon dating method

Robert D. Francis
California State University
Department of Geological Sciences
Long Beach, CA 90840-4809
USA

Sulfides in mafic and ultramafic magmas

Peter W. Francis
The Open University
Department of Earth Sciences
Walton Hall
Milton Keynes, MK7 6AA
UK

Volcanism

Frederick A. Frey
Massachusetts Institute of Technology
Department of Earth, Atmospheric and Planetary Sciences
Cambridge, MA 02139-4307
USA

Elements: distribution

Silvia Frisia
Museo Tridentino di Scienze Naturali
Via Calepina 14
I-38100 Trento
Italy

*Calcium carbonate and the carbonic acid system;
Dolomite and dolomitization*

Carol D. Frost
University of Wyoming
Department of Geology and Geophysics
PO Box 3006, University Station
Laramie, WY 82071-3006
USA

Neodymium in sedimentary rocks

William S. Fyfe
University of Western Ontario
Department of Geology
Faculty of Science
London ON, N6A 5B7
Canada

Geochemistry; Mineralogy; Soil

Patrick K. Gallagher
The Ohio State University
Departments of Chemistry, and Mat. Sci. & Eng.
100 West 18th Avenue
Columbus, OH 43210-1173
USA

Thermogravimetry

L. Galois
Universités Paris 6 et 7
Laboratoire de Minéralogie et Crystallographie
Unité Associée au CNRS 09
Tour 16, 4, place Jussieu
F-75252 Paris Cedex 05
France

Elements: transition; Nickel

Heinz Gamsjäger
Institut für Physikalische Chemie
Montanuniversität Leoben
Franz-Josef-Strasse 18
A-8700 Leoben
Austria

Charles A. Geiger
Mineral.-Petrograph. Institute
Universität Keil
Olshausenstr. 40
D-24098 Keil
Germany

T. M. Gerlach
US Geological Survey
Cascade Volcano Observatory
5400 MacArthur Blvd.
Vancouver, WA 98661
USA

Joris Gieskes
Scripps Inst. of Oceanography
Marine Research Division
9500 Gilman Drive
La Jolla, CA 92093-0215
USA

William E. Glassley
Lawrence Livermore National Laboratory
Earth Sciences Department, L 202
Livermore, CA 94550
USA

James L. Gooding
1022 Willowvale Dr.
Seabrook, TX 77586
USA

J. N. Goswami
Physical Research Laboratory
Narrangpura
Ahmedabad 380 009
India

K. Govindaraju
3 Chemin de Ludres
F-54180 Houdemont
France

David W. Graham
Ocean & Atmospheric Sciences
Oregon State University
Corvallis, OR 97331-5503
USA

Equilibrium; Solubility

Dana T. Griffen
Brigham Young University
Geology Department
PO Box 25183
Provo, UT 84602-5183
USA

Crystal chemistry; Ionic radii

John C. Groen
Texaco Research & Development
P.O. Box 509
Beacon, NY 12508
USA

Tungsten

Ethan L. Grossman
Texas A&M University
Department of Geology
College Station, TX 77843
USA

Oxygen isotopes

Martin Hale
International Institute for Aerospace
Survey and Earth Sciences (ITC)
Kanaalweg, 3
NL-2628 EB Delft
The Netherlands

Natural resources; Ore deposits

A. Hall
Department of Geology
Royal Holloway College
Egham
Surrey, TW20 0EX
UK

Nitrogen

Keith Hannan
MIM Exploration Pty. Ltd.
LMB 100
GPO Box 1042
Brisbane, Queensland 4001
Australia

Sulfur isotopes in geochemistry

Russell S. Harmon
Branch Chief, Terrestrial Sciences
US Army Research Office
AMXRO-EN, PO Box 12211
Research Triangle Park, NC 27709-2211
USA

Atomic number

T. Mark Harrison
University of California
Dept. of Earth and Space Sciences
Los Angeles, CA 90024
USA

⁴⁰Ar-³⁹Ar dating method

Nucleosynthesis

Geochemical reference materials

Helium isotopes

R. Hellmann
 Crustal Fluids Group
 LGIT-IRIGM
 BP 53X
 F-38041 Grenoble-Cedex 9
 France

Nancy W. Hinman
 University of Montana
 Department of Geology
 Missoula, MT 59812-1019
 USA

Elisabeth A. Holland
 MPI für Biogeochemie
 Tatzendpromenade 1a
 D-07745 Jena
 Germany

Ian E. Hutcheon
 University of Calgary
 Geology & Geophysics
 Calgary AL, T2N 1N4
 Canada

Philippe Ildefonse
 Laboratoire de Mineralogie-Cristallographie
 Universités Paris 6 et 7
 4 Place Jussieu, case 115
 F-75252 Paris Cedex 05
 France

Eugene S. Ilton
 Lehigh University
 Department of Earth and Environmental Sciences
 31 Williams Drive
 Bethlehem, PA 18015-3188
 USA

David R. Janecky
 Los Alamos National Laboratory
 Chemical Sciences and Technology, CST-7, MS J514
 Environmental Science & Waste Technology Group
 Los Alamos, NM 87545
 USA

Jan Jehlička
 Institute of Geochemistry, Mineralogy and Mineral
 Resources
 Charles University
 Albertov 6
 128 43, Prague 2
 Czech Republic

Stoichiometry

R. Basil Johns
 University of Melbourne
 School of Chemistry
 Parkville, Victoria 3052
 Australia

Occurrence of organic facies

Vidojko Jovič
 Faculty of Mining & Geology
 Department of Geochemistry
 Djušina 7
 11000, Belgrade
 Yugoslavia

*Epigenesis; Hypogene; Rocks; Supergene; Tellurium;
 Thallium*

Robert J. Kamilli
 Southwest Field Office
 US Geological Survey, Geologic Division
 520 North Park Avenue, Suite 355
 Tucson, AZ 85719
 USA

Paragenesis

Juha Karhu
 Geological Survey of Finland
 P.O. BOX 96
 FIN-02151, Espoo
 Finland

Carbon isotopes

Ronald S. Kaufmann
 RUST E&G
 1515 N Federal Highway #405
 Boca Raton, FL 33432
 USA

*Astatine; Bromine; Chlorine; Elements: halogen; Fick's law;
 Fluorine; Hydrogen*

M. Elaine Kennedy
 Loma Linda University
 Geoscience Research Institute
 Loma Linda, CA 92350
 USA

Elements: trace; Paleoenvironments

Ray Kenny
 Dept. of Geology
 New Mexico Highlands University
 Las Vegas, NM 87701
 USA

Hydrologic cycle

Hans Keppler
 Bayerisches Geoinstitut
 University of Bayreuth
 PF 10 12 51
 D-95440 Bayreuth
 Germany

Crystal field theory

Nitrogen cycle

Sedimentary fluids

Aluminum

Chromium; Selenium

Americium; Curium; Neptunium

Black shales and sapropels

- | | |
|---|---|
| Ross C. Kerr
Australia National University
Research School of Earth Sciences
Canberra, ACT 0200
Australia | D. Lal
University of California
Scripps Institution of Oceanography
Graduate Department
La Jolla, CA 92093-0208
USA |
| Richard M. Kettler
University of Nebraska
Department of Geosciences
Lincoln, NE 68508
USA | <i>Mass transfer</i>
Cosmic elemental abundances; Carbon-14 dating |
| M. A. K. Khalil
Department of Physics
Portland State University
P.O. Box 751
Portland, OR 97207-0751
USA | <i>Chelation</i>
Claude Largeau
Université Pierre & Marie Curie (Paris VI)
Lab. de Biogéochimie Isotop.
(URA 196 CNSR-INRA)
place Jussieu
F-75252 Paris
France |
| Erich Königsberger
Institut für Physikalische Chemie
Montanuniversität Leoben
A-8700 Leoben
Austria | <i>Earth's atmosphere</i>
Anton P. le Roex
University of Cape Town
Department of Geological Sciences
Library Road, Upper Campus
Rodebosch, 7700
South Africa |
| Jan Košler
Charles University
Department of Geochemistry and Mineralogy
Albertov 6
Prague 2, 128 43
Czech Republic | <i>Equilibrium constant; Solid solution</i>
Mid-ocean ridge basalt (MORB) |
| R.V. Krishnamurthy
Department of Geology
Rood Hall
Western Michigan University
Kalamazoo, MI 49008
USA | <i>Metamorphic environments: chemical mobility;
Neodymium in igneous rocks</i>
Ernest B. Ledger
Stephen F. Austin State University
PO Box 13011
Department of Geology
Nacogdoches, TX 75962
USA |
| S. Krishnaswami
Physical Research Laboratory
Earth Science Division
Navrangpura
Ahmedabad, 380 009
India | <i>Counters</i>
Ralf Littke
RWTH Aachen
Lehrstuhl für Geologie, Geochemie und
Lagerstätten des Erdöls und der Kohle
Lochnerstrasse 4 20
D-52056 Aachen
Germany |
| Keith A. Kvenvolden
US Geological Survey MS 999
345 Middlefield Road
Menlo Park, CA 94025
USA | <i>Hydrogen isotopes</i>
Austin Long
Laboratory of Isotope Geochemistry
Department of Geosciences
University of Arizona
Gould-Simpson Bldg.
Tucson, AZ 85721
USA |
| | <i>Coal: vitrinite reflectance and maturity</i> |
| | <i>Carbon; Tritium</i> |
| | Leon E. Long
University of Texas at Austin
Department of Geological Sciences
P.O. Box 7909
Austin, TX 78713-7909
USA |
| | <i>Biogenic methane and gas hydrate</i>
Lead: stable isotopes; Rubidium-strontium method |

Steven W. Lonker
3731 Kanawha St. N.W.
Washington, DC 20015
USA

Geothermal systems

Christian Ludwig
Department of Chemistry
University of Bern
Bern
Switzerland

Surface geochemistry

Virgil W. Lueth
New Mexico Bureau of Mines & Mineral Resources
New Mexico Institute of Mining & Technology
801 Leroy Place
Socorro, NM 87801
USA

Antimony; Bismuth

Robert W. Luth
University of Alberta
Geology
Edmonton AL, T6G 2E3
Canada

Phase equilibria

Hans G. Machel
Department of Earth and Atmospheric Science
University of Alberta
Edmonton, Alberta T6G 2E3
Canada

Sulfate reduction

Stephen A. Macko
University of Virginia
Department of Environmental Sciences
Charlottesville, VA 22903
USA

Organic matter in fossils

Helen Mango
Castleton State College
Department of Natural Sciences
Castleton, VT 05735
USA

Complexes; Silver

Brian D. Marshall
US Geological Survey
Denver Federal Center
MS 963
Denver, CO 80225
USA

Dating methods; Potassium–calcium decay system;

C. Marshall
PO Box 280931
Lakewood, CO 80228
USA

Elements: transition

Gerald Matisoff
Case Western Reserve University
Department of Geological Sciences
10900 Euclid Avenue, AW Smith #112
Cleveland, OH 44106-7216
USA

Phosphorus

William F. McDonough
Department of Earth & Planetary Sciences
Harvard University
20 Oxford Street
Cambridge, MA 02138
USA

Earth's core

Scott M. McLennan
Department of Earth and Space Sciences
State University of New York at Stony Brook
Stony Brook, NY 11794-2100
USA

Cerium; Dysprosium; Earth's continental crust; Elements: lanthanide series, rare earths; Erbium; Europium; Gadolinium; Geochemical classification of the elements; Geochemistry of sediments; Holmium; Lanthanum; Lutetium; Neodymium; Praseodymium; Promethium; Samarium; Scandium; Terbium; Thulium; Ytterbium; Yttrium

Annemarie Meike
Lawrence Livermore National Laboratory
L-201 Geophysical Sciences Program
Livermore, CA 94551
USA

Mineral defects

Scott Messenger
Analytical Microscopy Group; B222/A113
National Institute of Standards and Technology
Gaithersburg, MD 20899
USA

Organic matter in meteorites

Martin Mihaljević
Charles University
Department of Geochemistry
Albertov 6
128 43, Prague 2
Czech Republic

Acid deposition; Lead; Mercury; Zinc

Douglas L. Miles
Group Manager, Analytical Geochemistry
British Geological Survey
Keyworth
Nottingham, NG12 5GG
UK

Laser ablation–inductively coupled plasma–mass spectrometry

David W. Mittlefehldt
C-23 Lockheed Martin SO
2400 NASA Road
Houston, TX 77058
USA

*Calcium; Cesium; Elements: alkali and alkaline earth;
Francium; Magnesium; Potassium; Sodium*

Carla W. Montgomery
Northern Illinois University
Department of Geology
De Kalb, IL 60115
USA

*Electron capture; Geochronology and radioisotopes;
Isotope dilution; Samarium-neodymium*

T. A. Moore
Coal Research Ltd.
P.O. Box 29-415
Ilam, Christchurch
New Zealand

Coal: organic petrography; Coal: types and characteristics

John W. Morgan
1712 Rangeview Drive
Fort Collins, CO 80524
USA

Osmium; Rhenium; Rhenium-osmium dating method

Guillaume Morin
Laboratoire de Minéralogie
Université Paris 6
Tour 16/2, 4, Place Jussieu
F-75252 Paris Cedex 05
France

Magnetism

Joan O. Morrison
Canadian Environmental Research and Training Institute
Niagra Falls ON, L2G 7B7
Canada

*Diagenesis; Paleoproductivity; Paleotemperatures;
Strontium in sedimentary rocks*

Carl O. Moses
Lehigh University
Department of Earth and Environmental Sciences
Bethlehem, PA 18015-3188
USA

Acids and bases; Enthalpy; Entropy; Free energy; Water

Richard W. Murray
Department of Earth Sciences
Boston University
675 Commonwealth Avenue
Boston, MA 02215
USA

Geochemistry of sediments

Charles W. Naeser
US Geological Survey, MS 926A
National Center
12201 Sunrise Valley Drive
Reston, VA 22092
USA

Fission track analysis

Nancy D. Naeser
US Geological Survey, MS 926A
National Center
12201 Sunrise Valley Drive
Reston, VA 22092
USA

Fission track analysis

Bartholomew S. Nagy (deceased)

Oklo natural nuclear reactor

A. M. R. Neiva
Departamento de Ciencias da Terra
Universidade de Coimbra
Apartado 3014
P-3049 Coimbra Cedex
Portugal

Niobium; Tantalum; Tin

Roger L. Nielsen
Oregon State University
Department of Geosciences
Wilkinson Hall 104
Corvallis, OR 97331-5506
USA

Trace element partitioning models

Mary P. Neu
Los Alamos National Laboratory
Chemical Sciences & Technology Division, CST-7
Mail Stop J514
Los Alamos, NM 87545
USA

Americium; Curium; Neptunium

Nathaniel E. Ostrom
Michigan State University
Department of Geological Sciences
206 Natural Science Building
East Lansing, MI 48824-1115
USA

Nitrogen isotopes

Peggy H. Ostrom
Michigan State University
Department of Geological Sciences
206 Natural Science Building
East Lansing, MI 48824-1115
USA

Nitrogen isotopes

Maurice Pagel
 Département des Sciences de la Terre
 Bt 504, Université Paris-XI
 F-91405 Orsay Cedex
 France

Geothermometers

Herbert Palme
 Universität zu Köln
 Mineralogisch-Petrographisches Institut
 Zülpicherstrasse 49b
 50674, Köln Germany

*Earth's formation and geochemical evolution;
 Elements: chalcophile; Elements: siderophile*

Cynthia E. A. Palmer
 Lawrence Livermore National Laboratory
 P.O. Box 808, L-231
 Livermore, CA 94550
 USA

*Actinium; Berkelium; Californium; Einsteinium; Fermium;
 Lawrencium; Mendelevium; Nobelium*

P. Jonathan Patchett
 University of Arizona
 Department of Geosciences
 Gould-Simpson Building #77
 Tucson, AZ 85721
 USA

Hafnium; Lutetium-hafnium decay system

Charles G. Patterson
 PO Box 3007
 El Dorado Springs, CO 80025
 USA

Oxidation-reduction

Michael Perfit
 Department of Geology
 University of Florida
 Gainesville, FL 32611
 USA

Earth's oceanic crust

Kenneth E. Peters
 Mobil E&P Technical Center
 P.O. Box 650232
 Dallas, TX 75265-0232
 USA

*Biomarker: aliphatic; Biomarker: assessment of thermal
 maturity; Rock-Eval pyrolysis;*

Lloyd M. Petrie
 189 Burke Avenue
 Roseville, MN 55713
 USA

Manganese

R. P. Philp
 University of Oklahoma
 School of Geology and Geophysics
 810 Energy Center, 100 East Boyd
 Norman, OK 73019-0628
 USA

Petroleum: surface geochemistry

David A. Pickett
 Center for Nuclear Waste Regulatory Analyses
 Southwest Research Institute
 6220 Culebra Rd.
 San Antonio, TX 78238-5116
 USA

Protactinium

Philip J. Potts
 The Open University
 Department of Earth Sciences
 Walton Hall
 Milton Keynes, MK7 6AA
 UK

*Analytical techniques; Atomic absorption spectrometry;
 Synchrotron X-ray fluorescence analysis;
 X-ray fluorescence analysis*

Stephen A. Prevec
 Hugh Allsopp Lab, BPI (Geophysics)
 University of the Witwatersrand
 P.O., WITS 2050 (Private Bag 3)
 Johannesburg
 South Africa

Radioactivity

Alain Prinzhofer
 Institut Français du Pétrol
 Division Géologie-Géochimie
 1 & 4, avenue de Bois-Préau, BP 311
 F-92506 Rueil-Malmaison Cedex
 France

Natural gas

Matthias Radke
 KFA Jülich (ICG-4)
 P.O. Box 1913
 D-52425 Jülich 1
 Germany

Biomarker: coals

D. G. Rancourt
 University of Ottawa
 Ottawa-Carleton Geoscience Centre
 Department of Physics
 Ottawa, K1N 6N5
 Canada

Mössbauer spectroscopy; Quantum numbers

Andrew T. Revill
 CSIRO Division of Oceanography
 GPO Box 1538
 Hobart, Tasmania 7001
 Australia

*Gas chromatography-mass spectrometry (GC-MS);
 Oil seeps and coastal bitumens; Oil shales*

Jeremy P. Richards
 University of Leicester
 Department of Geology
 Leicester, LE1 7RH
 UK

Sulfate minerals; Sulfide minerals; Sulfosalt minerals

Jean M. Richardson
Lakefield Research
195 Concession Street
Box 4300
Lakefield, ON K0L 2HO
Canada

Onuma diagrams; Sampling

W. Ian Ridley
US Geological Survey
PO Box 25046, MS 973
Lakewood, CO 80225
USA

Earth's mantle geochemistry; Elements: incompatible

Mark J. Rigali
University of Arizona
Department of Geosciences
Tucson, AZ 85721
USA

Oklo natural nuclear reactor

Stephen Roberts
Department of Geology
University of Southampton
Southampton, SO17 1BJ
UK

Micro-Raman spectroscopy

Peter C. Rock
University of California, Davis
Department of Chemistry
Davis, CA 95616
USA

*Critical points; Geochemical thermodynamics;
Gibbs–Duhem equation; Standard states*

Michel Rohmer
Université Louis Pasteur
Institut le Bel
4 rue Blaise Pascal
F-67070 Strasbourg Cedex
France

*Biomarkers: lipid, bacterial chemical fossils; Lipids
(eubacteria and archebacteria)*

Arthur W. Rose
218 Deike Bldg.
Pennsylvania State University
University Park, PA 16802
USA

Geochemical exploration; Radium; Radon

David A. Rothery
The Open University
Department of Earth Sciences
Walton Hall
Milton Keynes, MK7 6AA
UK

Remote sensing

Roberta L. Rudnick
Department of Earth & Planetary Sciences
Harvard University
20 Oxford Street
Cambridge, MA 02138
USA

Elements: large-ion lithophile

Joaquin Ruiz
University of Arizona
Department of Geosciences
Tucson, AZ 85721
USA

Analytical geochemistry; Geochemical tectonics

Wolfgang H. Runde
Los Alamos National Laboratory
Chemical Sciences & Technology Division, CST-7
Mail Stop J514
Los Alamos, NM 87545
USA

Americium; Curium; Neptunium; Polonium

Jeffrey G. Ryan
University of South Florida
Geology Department
4202 E. Fowler Avenue
Tampa, FL 33620
USA

Beryllium

V. Salters
Florida State University
Department of Geology
Tallahassee, FL 32306
USA

Elements: high field strength

R. G. Schaefer
Institut für Erdöl und Organische Geochemie
Forschungszentrum Jülich GmbH
D-52425 Jülich
Germany

*Petroleum; Petroleum: types, occurrences and reserves;
Petroleum: kinetic modeling;*

Martin A. A. Schoonen
Earth and Space Science Department
SUNY at Stony Brook
Stony Brook, NY 11794-2100
USA

Sulfur; Sulfur cycle

Erich Schroll
Institute of Mineralogy and Crystallography
University of Vienna
A-1090 Vienna
Austria

Gallium; Germanium; Indium

Mitchell Schulte
NASA Ames Research Center
MS 239-4
Moffett Field, CA 94053
USA

Thermochemistry

Jeffrey S. Seewald
Department of Marine Chemistry and Geochemistry
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
USA

Laboratory simulations of oil and natural gas formation

Steven C. Semken
Diné College, Shiprock
Navajo Dryland Environments Laboratory
POB 580
Shiprock, Navajo Nation, NM 87420-0580
USA

Oxygen

Jane C. Shearer
Research Office
University of Canterbury
Private Bag 4800
Christchurch
New Zealand

Coal: organic petrography; Coal: types and characteristics

Nobumichi Shimizu
Department of Geology and Geophysics
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
USA

Ion microprobe

William Shotyk
Geological Institute, University of Berne
Baltzerstrasse 1
CH-3012 Berne
Switzerland

Peat

Elisabeth L. Sikes
Antarctic Cooperative Research Centre
University of Tasmania
GPO Box 252-80
Hobart, Tasmania 7001
Australia

*Paleo-sea surface temperature estimations:
Organic geochemistry and paleoclimates*

E. Craig Simmons
Department of Chemistry & Geochemistry
Colorado School of Mines
Golden, CO 80401
USA

Rubidium; Strontium

Bernd R. T. Simoneit
Oregon State University
College of Oceanic & Atmospheric Sciences
Oceanography Admin. Building 104
Corvallis, OR 97331-5503
USA

*Biomarker: aromatic; Biomarker: higher plant;
Petroleum: hydrothermal*

Abigail M. Smith
University of Otago
Department of Marine Sciences
PO Box 56
Dunedin
New Zealand

Carbonate sediments

Kathleen S. Smith
US Geological Survey
Denver Federal Center
MS 973
Denver, CO 80225-0046
USA

Barium; Cadmium; Geoavailability

Gregory A. Snyder
Planetary Geosciences Institute
Department of Geological Sciences
University of Tennessee
Knoxville, TN 37996-1410
USA

Meteorites; Periodic Table; Vanadium

Thomas Staudacher
Institut de Physique du Globe de Paris
Observatoire Volcanologique du Piton de la Fournaise
14 Route Nationale 3-27ème km
F-97418 La Plaine des Cafres
France

*Argon; Elements: noble gases; Helium; Krypton; Neon;
Xenon*

Heinz G. Stosch
Institut für Petrographie und Geochemie
Universität Karlsruhe
Kaiserstrasse 12
D-76128 Karlsruhe
Germany

Elements: lithophile

Kurt Stüwe
Institut für Geologie
Universität Graz
Heirnrichstr 26
A-8010 Graz
Austria

Diffusion

Roger E. Summons
Mineral Resources
GPO 378
Canberra, ACT 2601
Australia

*Compound-specific stable isotope analysis;
Precambrian organic matter*

Stuart Ross Taylor
Australian National University
Nuclear Physics R.S. Phys. S.
Canberra, AC 2601
Australia

Earth's continental crust

Peter van Calsteren
The Open University
Department of Earth Sciences
Walton Hall
Milton Keynes, MK7 6AA
UK

*Ion exchange chromatography;
Thermal ionisation mass spectrometry*

R. K. Varma
Physical Research Laboratory
Ahmedabad, 380 009
India

Elementary particles

Philippe Vidal
Institut National des Sciences de l'Univers
3, rue Michel-Ange
B.P. 287 F-75766 Paris Cedex 16
France

Uranium-lead thorium-lead decay system

Benoît Villemant
L.G.C.S.
UPMC(P6), IPGP et CNRS (URA 1758)
Case Postale 109
4, place Jussieu
F-75252 Paris Cedex 05
France

Elements: actinide series

John K. Volkman
C.S.I.R.O Division of Oceanography
GPO Box 1538
Hobart, Tasmania 7001
Australia

*Biogeochemistry; Hydrocarbons; Organic geochemistry;
Steroidal compounds*

Christiane R. Wagner
Laboratoire de Pétrologie
Université Paris 6
UPMC, Tour 26, E3
4, Place Jussieu
F-75252 Paris Cedex 05
France

Electron microprobe; Scanning electron microscope

Stuart G. Wakeham
Skidaway Institute of Oceanography
10 Ocean Science Circle
Savannah, GA 31411
USA

*Organics: contemporary degradation and preservation;
Organics: sources and depositional environments*

Clifford C. Walters
Mobil E&P Technical Center
P.O. Box 650232
Dallas, TX 75265-0232
USA

Biomarker: aliphatic; Oil-oil and oil-source rock correlation

Richard B. Wanty
US Geological Survey
Denver Federal Center
PO Box 25046, MS 973
Lakewood, CO 80225
USA

Eh-pH relations

Jenny G. Webster
School of Environmental and Marine Science
University of Auckland
Private Bag 92021
Auckland
New Zealand

Arsenic; Gold

Homer C. Weed
Lawrence Livermore National Laboratory
Earth Sciences Department
Livermore, CA 94550
USA

Thixotropy

Dietrich H. Welte
Forschungszentrum Jülich GmbH
ICG-4
D-52425 Jülich
Germany

Petroleum: types, occurrences and reserves

Richard F. Wendlandt
Colorado School of Mines
Department of Geology and Geoengineering
1516 Illinois St.
Golden, CO 80401-1887
USA

Geothermometry and geobarometry

T. M. Whitworth
New Mexico Bureau of Mines and Mineral Resources
New Mexico Institute of Mining and Technology
Socorro, NM 87801
USA

Clay membranes; Clay minerals: ion exchange

Mark A. Williamson
Senior Geochemist
Adrian Brown Consultants, Inc.
333 W. Bayuad
Denver, CO 80223
USA

Thomas J. Wolery
Lawrence Livermore National Laboratory
Earth Sciences Department
PO Box 808, L-219
Livermore, CA 94550
USA

*Activation energy; activation enthalpy; activation volume;
Activity and activity coefficients; Debye–Hückel equation;
Electrolyte theory*

Ian P. Wright
Department of Earth Sciences
The Open University
Walton Hall
Milton Keynes, MK7 6AA
UK

Gas source mass spectrometry

Grant M. Young
University of Western Ontario
Department of Geology
London ON, N6A 5B7
Canada

Copper; Iron

Precambrian atmosphere

Jae-Young Yu
Geol. Coll. Natural Science
Kangweon National University
Chuncheon
Kangweon-Do, 200-701
Korea

*Clapeyron's equation; Electronegativity; Exsolution;
Van der Waals force*

Youxue Zhang
University of Michigan
Department of Geological Sciences
Ann Arbor, MI 48109-1063
USA

Chemical kinetics; Crystal growth

Preface

Geochemistry uses the methods and philosophy of chemistry to explore and understand the Earth from the most basic, elementary levels, to constrain and comprehend the evolution of the planet and life on it. By looking deeper into the Earth's constituents and their planetary systems and cycles, scientists are able to verify theories on the Earth's formation and, by corollary, on the formation of other planets in the universe. Because the science of geochemistry involves detailed, intensive examinations of pieces of the planet, the subject touches on many aspects of other scientific explorations, such as the origin of life, environmental contamination and waste management, weather anomalies, predicting Earth tremors and volcanoes, as well as finding mineral and organic ores.

Geochemistry has evolved from a nineteenth century aim of analyzing the composition of terrestrial materials and ore deposits, to a twentieth century triumph of beginning to understand the dynamic processes of the nature of the Earth and other 'Earth-like' celestial bodies.

The *Encyclopedia of Geochemistry* is designed as a complete reference text for the evolving field of geochemistry. Over 200 top scientists, experts in their fields, have written over 340 separate topics on different aspects of geochemistry including Age-Dating Techniques, Organics, Trace Elements, Isotopes, High and Low Temperature Geochemistry and Ore Deposits. This reference text covers all aspects of geochemistry, so that an expert in one field can look up information in other fields, or a student can find general information to initiate a research project, or a non-geochemist can investigate a topic that is of interest. Each topic has its own reference list, carefully selected by an expert in the field, to lead the reader to other articles on that topic. The topics are arranged alphabetically and the indexes are comprehensive and extensive. Each element has its own separate entry. Analytical instruments used to refine geochemical techniques are described.

The Importance of Geochemistry

Geochemists study the distribution and localization of elements and their isotopes within widely different environments, as well as the pathways and processes that lead to their modern or ancient migrations. Those processes occur within the atmosphere, hydrosphere, lithosphere, mantle and core, at temperatures that range from nearly zero K to $>10^3$ K. In the framework of plate tectonics, the late twentieth century Earth

Science paradigm, geochemistry occupies an essential niche in the multidisciplinary studies that have made possible that quantum leap in the understanding of science as a whole.

Anticipating the twenty-first century, Earth scientists face urgent demands for understanding, action and cures for long-term environmental pollution, a truly global problem where geochemists will play an ever increasing key role. Another area of global concern is that of raw materials and sustainable development. Here, too, the geochemists of the future will be playing significant parts in the maintenance of a habitable and civilized planet.

Geochemistry has already contributed its greatest gift to humankind, its ability to determine so-called 'absolute' dates for the events of planetary and Earth history. This gift is of inestimable value, both in practical sciences such as petroleum geology and in humanity's very philosophy. We can now say with a high degree of certainty that we inhabit a planet that came into existence at the same time as the Sun (our own special star) and all the other planets of the solar system, that is, about four and a half billion years ago. We now have good evidence that the first life on this planet was in existence by at least four billion years ago. And furthermore, from this initial event, the beginning of self-reproducing organisms, and onwards right up to the present day, there has been no interruption in the continuity of the thread of both physical and biological evolution. Dinosaurs and other creatures have become extinct from time to time, but the ancient geochemical environments, though gradually changing, have always survived to permit the continuity of some forms of life. The importance of this fact for human philosophy should never be forgotten. In spite of doomsday warnings, the 'end' is not 'nigh'. The Earth and its essential inhabitants have always survived. The twenty-first century should nevertheless prove interesting. Certainly, it will be challenging.

The discovery of geochronology by the geochemists has made possible also epoch-making discoveries in the kindred disciplines of the Earth Sciences. Since early in the twentieth century, geomagnetic reversals were known in the Earth's field, but with geochronology they are now quantified into a distinctive magnetic chronology of its own (see *Benchmark*, vol. 54, by Kennett, 1980). The science of paleoclimatology was revolutionized when George Kukla determined that the magnetic reversals of the Czechoslovakian loess paralleled those of China (both continental products) and then with deep-sea

deposits, already dated by the geochemists. And then the deep-sea stratigraphy dating was found to run exactly parallel with the calculated incoming solar radiation as determined 80 years ago by Martin Milanovitch. This was proved in the fundamental ‘Earth laws’, number 1, the principle of solar and planetary dependence. Incorporated into Vail’s ‘EXXON stratigraphy’, it is now in daily use by petroleum geologists in their worldwide search for hydrocarbons. Astronomic cyclicity is now a fundamental facet of Earth Sciences.

Geochemistry’s gift of quantitative chronology also provides the ‘teeth’ in studies of rates of change in sedimentology, stratigraphy, geomorphology and tectonics. Rates of inflow of asteroids provide a basis for Rampino’s ‘Shiva hypothesis’, and for the organic extinction theories of paleontologists. The ‘great gifts’ seem endless.

An historical note is appropriate in special appreciation of ‘Chuck’ Hutchinson, who saw many of the early encyclopedias of this series into the press. Without his constant encouragement they would never have been seen to completion. The senior editor (RWF) began his association with the old Van Nostrand Company in the early 1960s when it was then located in Princeton, NJ. Successive corporate arrangements over the years have led to name and style changes among publishers, but Hutchinson stayed with the team until the 1980s. Under

his supervision appeared the first version of the present work, entitled *The Encyclopedia of Geochemistry and Environmental Sciences* (1972, 1321 pp). In spite of its monstrous size, it sold many thousands of copies worldwide. Our new volume is not only totally reworked, but benefits from new space provided by trimming off the bulk of the hydrology and environmental material, each of which now receives separate volume status.

Chuck Hutchinson not only saw all the early encyclopedias to fruition but (with Milo Dowden) helped create the *Benchmark Papers in Geology*, a series of reviews and reprint volumes (mostly of 300–500 pages each) that finally reached the astonishing total of 90 volumes (1972–1985). Most of these are now in the major libraries and provide ready access to the classical and often rare papers. Volumes that relate to geochemistry include: *Marine Evaporites* (Kirkland and Evans, 1973), *Germanium* (Weber, 1973), *Origin of Life* (Kvenvolden, 1974), *Geochemistry of Water* (Kitano, 1975), *Geochemistry of Iron* (Lepp, 1975), *Geochemistry of Boron* (Walker, 1975), *Sea Water: major elements* (Drever, 1977), *Geochemistry of Bismuth* (Angino and Long, 1979), *Geochemistry of Organic Molecules* (Kvenvolden, 1980), *Dolomitization* (Zenger and Massullo, 1982), and *Chemical Hydrogeology* (Back and Freeze, 1983).

Rhodes W. Fairbridge and Clare P. Marshall

Acknowledgements

We wish to thank the scientists who took the time and energy to review a large portion of the articles in this publication. Their keen eyes assured accuracy and clarity in the topics reviewed, and often found and deleted redundancy. The following people, among others, reviewed articles for this volume: William Bourcier, David Clark, Carol Frost, William Glassley, J.R. Hulston, Ian Hutcheon, David Janecky, Richard Kettler, Ralph Kretz, Mark Kurz, Kenneth R. Ludwig, Brian Marshall, Christopher Martens, Brian Mason, William McDonough, Scott McLennan, Annemarie Meike, David Mittlefehldt, Richard Murray, Mary Neu, Zell Peterman, Philip Potts, Roberta Rudnick, Wolfgang Runde, Jeffrey Ryan, Peter A. Sabine and C.Drew Tait.

Advisory Board: Frederick Frey, William Fyfe, Alain Huc, John Volkman.

Enthusiam and editorial support (for CPM): William Casey, the late Cesare Emiliani, Scott McLennan, Annemarie Meike, Carl Moses.

General and helpful advice on which topics to include and on finding authors for topics has been provided by the following scientists: Francis Albareda, Alain Baronnet, Fernando Bea, Will Berelson, F. Donald Bloss, Donald Bowes, Tom Boyd, Susan Carroll, Patricia Dove, Charles Geiger, Roland Hellmann, Ian Hutcheon, Eugene Ilton, Erich Königsberger, Keith Kvenvolden, Devendra Lal, Ian Lange, Steve Lonker, Brian Marshall, P. Marion, Annemarie Meike, William McDonough, Scott McLennan, Christophe Monnin, Roger Nielsen, Herbert Palme, Philip Potts, William Shotyk, Kathleen Smith, Michele Tuttle, Cornelis van der Weijden, Benoit Villemant, Eugene Ulmer, Hatten Yoder, William White.

To the article authors, we want to express our profound appreciation and gratitude for their patience and wholehearted cooperation.

We also wish to thank Ian Francis and his associates at the former Chapman and Hall, who were constantly helpful.